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ANALYTICAL STUDY OF SPIN

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ANALYTICAL STUDY OF SPIN /1***

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ABSTRACT. A method of spin calculation, investigated jointly by the Fluid Mechanics Institute of Lille and the ONERA, is discussed. The aerodynamic parameters were obtained from analytical wind tunnel measurements of the constant and variable derivatives, performed on the same model and used as basis in the calculation of aircraft motion, programmed on a digital computer. The object of these first calculations was to conform the free-spin results obtained in the vertical wind tunnel at Lille on a delta-60 aircraft model. The results obtained are analyzed and discussed.

1. Introduction /2

The purpose of this paper is to present results obtained in the first phase of an analytical study of spin, performed by the ONERA in collaboration with the Fluid Mechanics Institute of Lille at the request of the Technical Aeronautics Services.

The reasons for undertaking this study were discussed in a previous Colloquium of the AFITAE* two years ago (Ref.1) and will not be repeated here.

However, we should mention that analytical spin studies form part of the computation techniques currently in use by designers in the USA. This was shown by H.J.Wykes in a paper presented at a recent AGARD Meeting, which contained a comparison between calculations and free-flight spin tests for the F-100 aircraft (Ref.2).

The topic of our first study was to calculate the spin of a small delta aircraft model which, toward this end, was tested in free flight in the vertical wind tunnel of the IMFL**.

This manner of proceeding, by eliminating the uncertainties with respect to the scale effect and the inertia constants, permits a correct qualification of the computational method.

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1) ONERA (National Aerospace Research and Development Administration) Chatillon, France.

* French Association of Aeronautics and Space Engineers and Technicians.

** Institute of Fluid Mechanics, Lille.

*** Numbers in the margin indicate pagination in the foreign text.

The aerodynamic data are those obtained in conventional stationary and non-stationary tests with forced oscillations and in tests with forced rotation.

These analytical tests were performed in a horizontal wind tunnel on the model tested in the free-spinning wind tunnel, with the flow velocities being similar in both cases.

The calculation was carried out at the Automatic Computer Center of the ONERA using a digital computer and a general program of flight mechanics, according to an equation established by Bismut and Walden.

Two configurations were studied, one for entry into a stabilized spin and the other for recovery from the spin.

2. Notations

The notations used conform to the French Standard AFNOR X 02-105.

The reference trihedrons are shown in Fig.2 and the general notations in Fig.3*.

Special Notations

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α_r = deflection angle of the right elevon,
α_l = deflection angle of the left elevon,
N_0 = component of the aerodynamic moment about the axis of rotation Gz_0 (parallel to the direction of flow); Fig.5,
L_0 = component of the aerodynamic moment about Gx_0 perpendicular to Gz_0 and such that Gz_0 comes to lie in the plane of symmetry of the aircraft when φ_1 is zero,
Φ_1 = angle of roll (Fig.2a),
r_0 = angular velocity about Gz_0,
r_0^* = reduced angular velocity $\frac{r_0 l}{V}$ (*)

dimensionless coefficients:

$$C_{n_0} = \frac{N_0}{p/2\ V\ Sl}$$

$$C_{l_0} = \frac{L_0}{p/2\ V\ Sl}$$

δ_x = relative course: angle of the horizontal projection of Gx_1 made with the radius of spin.

(*) Note: The asterisk denotes the reduced angular velocities.

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* Figures not contained in original.

3. Model

The model, in a stylized manner, represents a delta aircraft of 60° sweep-back without horizontal tail unit, and is equipped with elevons extending over the entire span.

The basic geometric and mass characteristics are given in Fig.4.

4. Testing Facilities

The free-flight spin tests were made in the vertical wind tunnel of the IMFL.

The technique of these tests, developed by Gobeltz, is described in detail elsewhere (Ref.4).

Motion-picture photographs are taken of the model in flight; frame-by- /4
frame work-up permits restoring the trajectory of its center of gravity and the defined attitudes of the model as a function of time, by the following means:

horizontal projection of the trajectory, the radius of spin, the rate of descent, and the period of spin;

longitudinal and transverse trim and relative course.

4.2 Analytical Tools

4.2.1 Wind Tunnels

The stationary measurements were made in the IMFL horizontal wind tunnel of 2.4 m diameter.

The nonstationary measurements in forced oscillations and rotations were made in a small horizontal wind tunnel of 1 m diameter at the ONERA in Chalais-Meudon.

4.2.2 Mounting in the Test Section

The methods of stationary and nonstationary measurements under forced oscillations are of the conventional type and will not be discussed here (Ref.3); only the measurements under forced rotation will be given. These measurements had the object of defining the autorotation regimes, complemented by measuring the components of the resultant moment as a function of the rate of rotation, in an interval comprising the value of the autorotation regime.

Two different model suspensions were used (Fig.5); in both cases, the model was mounted to the extremity of a rotating sting with its axis parallel to the direction of flow and passing through the homologous point of the center of gravity of the aircraft.

One of these mountings gives the measurement of the moment N_0 about the axis of rotation. Basically, this setup comprises an electric motor which imparts the motion; this motor is mounted on a rocking cradle and its stator is restrained by a strain-gage dynamometer.

The other setup provides the measurement of the moment L_0 (or M_0) about an axis rotating with the model and perpendicular to the axis of rotation. This measurement is made by means of a strain-gage dynamometer mounted upstream of the sting to the right of the aircraft center of gravity. Its readings are transmitted to the measuring instrument over a set of smooth rings and brushes.

For both arrangements, the measuring instruments are those used in stationary measurements.

The axis G_{x_0} is taken in the plane of symmetry of the aircraft when the angle of skidding, imposed on the model, is zero. The axis G_{y_0} is perpendicular to the plane $G_{x_0 z_0}$ and the trihedron $G_{x_0 y_0 z_0}$ is of the right-angle type.

To produce skidding, a rotation φ_1 is imparted to the model about the longitudinal axis G_{x_1}; the resulting angle of skidding j is given by /5

$$\sin j = -\sin \varphi_1 \cos \theta, \text{ with } \theta \text{ being the angle } \widehat{x_0 \, C_{x_1}}.$$

4.2.3 Corrections Made

The measurements of N_0 require no correction.

The rough measurements of L_0 carry an error produced by the dynamic and static unbalance and proportional to r_0^2.

This error can be eliminated from the measurements by making the model turn in both directions and using as result the half-difference of the values measured in each direction, for one and the same absolute value of r_0.

This manner of proceeding also eliminates the error due to an asymmetry of form or of leveling ($\Delta\Phi_{10} \neq 0$) of the model. However, the method is strictly valid only for symmetric configurations.

Nevertheless, the method is acceptable for asymmetric configurations of the elevons.

The order of magnitude of the correction is 20% of the value L_0, read at the instant at which the value of r_0 reaches its maximum. A more rigorous manner of proceeding would have been to determine this correction by measurements in a rarefied atmosphere.

The ratio of the projected surface of the model (wing plus fuselage), perpendicular to the wing planform, to the cross section of the test section of the small wind tunnel is about 6%.

A correction for the plug effect was determined for the coefficient C_{z_1}, in a comparison test with the same model in a wind tunnel of 3 m diameter; the magnitude of this correction is 12% by excess.

No correction was made to the other coefficients for lack of sufficient data for their evaluation, since no comparison tests had been made.

4.2.4 Accuracy of Measurements

The kinetic pressure, the velocities of flow, and of rotation are known to within about 2%.

The scattering of the test data for L_0 and N_0 in the presence of wind is 10 - 15 times the sensitivity threshold of the dynamometers. This dispersion is produced by reading difficulties due to the turbulence of the flow separated on the model.

A highly approximate error calculation leads to the following conclusions:
- relative error for the reduced velocity of autorotation, about 10%; /6
- relative errors for the inclinations $C_{l_{r_0}}$ and $C_{n_{r_0}}$, about 10 - 15%.

5. Results of Analytical Tests

5.1 Investigated Configurations

The measurements of N_0 were carried out as a function of the angular velocity, for various values of angle of attack, symmetric setting and asymmetric setting of the elevons, and of the angle of skidding.

The measurements of L_0 were made at only one incidence.

The total configurations investigated are shown in Fig.6.

5.2 Results

5.2.1 Measurements of N_0

These measurements demonstrated the presence of autorotation regimes.

The values of this regime were obtained with various factors:

Angle of attack (Figs.7 and 12). In the interval of $65^\circ \leq i \leq 90^\circ$, at $j = 0$ and symmetric setting of the elevons, there exists a stable autorotation regime whose angular velocity increases with the angle of attack.

The inclination $C_{n_{r_0}}$ about this regime doubles between 65 and 70° and then remains almost constant up to 90°.

At an incidence of 60° (Fig.9), the autorotation regime becomes unstable or vanishes as soon as the elevon setting is positive or zero:

$$r_0 > 0 \qquad \alpha_l - \alpha_r \geq 0.$$

With a setting in the opposite direction

$$\alpha_l - \alpha_r < 0,$$

two autorotation regimes exist, one stable and the other unstable.

The measurements in the neighborhood of the unstable regime were very difficult. In fact, since the drive gear was not irreversible and the speed of the motor was not under control of a prescribed regime, the slightest disturbance was sufficient for misaligning the rate of rotation. A more complete study is scheduled, using a new installation which is presently being designed.

Elevon setting (Fig.8). The angle of incidence was fixed at 80° and the skidding angle at zero. /7

A wash-out ($\alpha_l - \alpha_r < 0$, with $r_0 > 0$) will increase the rate of autorotation.

The observed increase is independent of the mean position of the elevons $\frac{\alpha_l + \alpha_r}{2}$.

Under the same condition, a wash-in ($\alpha_l - \alpha_r > 0$, with $r_0 > 0$) will lead to a reduction in the rate of autorotation.

This decrease becomes more noticeable with decreasing value of the mean position, which corresponds to a stalled elevator.

Angle of skidding (Figs.10, 12). The rate of autorotation varies in a practically linear manner, in the same direction as the skidding angle.

5.2.2 Coefficient C_{l_0} (Fig.11)

The measurements were made at only one incidence of 85° for both positions of the elevons. The variation in C_{l_0} with r_0^* is linear, and a value of the inclination of

$$C_{l_{r_0}} = 0.03$$

has been retained for calculating the flight mechanics.

5.2.3 Measurement of M_0

Longitudinal measurements about G_{y_0} perpendicular to $G_{x_0 z_0}$ were made at the same incidence of 85°. These measurements showed that the value of the nose-down moment increased slightly (by about 5% with the velocity of rotation).

Otherwise, the effectiveness of the elevator cancels practically between 70° and 90°.

6. Calculations

6.1 Method

A very general program of flight mechanics, applicable to either aircraft or rockets, was used.

This program was laid out for solving six equations of motion on a digital computer, using the Runge-Kutta method.

6.1.1 Aerodynamic Data /8

These data are represented in the form of the conventional dimensionless coefficients of force and moment, expressed by linear functions of the variables i, j, p_i^*, q_i^*, r_i^*, of the Mach number, and of the three effective ranges of the control surface.

In the expressions given in Fig.13, the coefficients of the variables or the aerodynamic derivatives can be expressed, in turn, by functions of the first and second degree in i and j.

In the specific problem treated here, this arrangement was used only for expressing the yawing moment due to the control surfaces and the damping of the yaw.

Note:

1) A greater flexibility in introduction of the data has recently been obtained: The data are presented in the form of numerical tables as a function of different variables, so that it is no longer necessary to apply analytical expressions.

2) It should be recalled that the ONERA presently is developing a method for measuring the inertia constants at the ground (Ref.7).

6.1.2 Calculation Results

The computational data, as a function of time, yield the following:
- the trajectory coordinates of the center of gravity along axes fixed with respect to the earth;
- the angles of attack, angle of skidding, and the Mach number;
- the direction cosines of the aircraft axes on the fixed trihedron;

the modulus of velocity of the center of gravity;
the angular velocity components
the corresponding accelerations
the components of the resultant force
} along the aircraft axes;
the velocity components along the fixed axes.

An auxiliary program makes it possible to convert the above results into the form of those given by the IMFL, namely, longitudinal and transverse trim, radius of spin, relative course, and period of spin, to which must be added the horizontal coordinates of the trajectory and the rate of descent which had already been calculated directly.

6.2 Application /9

Two cases were selected from the free-spin tests made at the IMFL, with the first corresponding to entry into a stabilized spin and the second to recovery from the spin.

The values of the aerodynamic data corresponding to these two cases are shown in Fig.14.

6.2.1 Entering a Stabilized Spin (Figs.15 - 17)

In the investigated configuration, the elevons are set to

$$\alpha_l = 0 \qquad \alpha_r = +20^\circ.$$

The calculations were carried out with two values of the initial velocity of rotation.

In both cases, in complete agreement with the free flight, the following variables were obtained:

- mean values of the transverse and horizontal trim;
- period of spin of the stabilized regime;
- rate of descent;
- relative course, whose values are closer to the free flight for the highest value of r_{oo}.

Relatively minor discrepancies were observed for the following:

- amplitudes of a short-period oscillation, which were greater for the longitudinal trim and weaker for the transverse trim;
- spin radii that differed considerably, although the magnitude of the spin radius remains relatively low, i.e., 10% of the reference chord.

In addition, the angular velocity components along the fixed axes p_1, q_1, r_1 were calculated from the results of free flight.

6.2.2 Spin Recovery (Figs.18 - 21)

The setting of the elevons

$$\alpha_{l} = +20^{\circ} \qquad \alpha_{r} = 0$$

is opposite to that of the above configuration.

The calculations made for three values of the derivative $C_{n_{J_1}}$ /10

$$0.08 \qquad 0.125 \qquad \text{and} \qquad 0.25$$

show the significance of this derivative.

The first value is that obtained from analytical measurements; the second value furnishes a better agreement with the free-flight results; the third value gives too rapid a recovery from spin.

The discrepancy between calculation and free flight is most likely due to the fact that the experimental value of $C_{n_{J_1}}$ results from a test at only one incidence (80°) whereas this coefficient obviously varies with the incidence which passes from 80° to 50° during the investigated phase.

7. Continuation of the Study

7.1 Comparison of Computational Data and Flight Tests

The above comparison showed that, despite the various gaps with respect to aerodynamic data, the computational results intersect the measurements on models in free flight with sufficient approximation, for both cases under consideration.

This made it possible to start a study as to the conditions of entering into and recovering from a spin, in continuation of the previous study and constituting the basic object of this particular research; an attempt of intersecting a flight test with calculation is in progress at present.

7.2 Measurements with Forced Rotation

Practical experiments with provisional assemblies have permitted the design and construction of an installation adapted to a wind tunnel of 2.5 - 3 m diameter.

This facility was designed to give the six aerodynamic force components over a wide range of incidence and skidding.

Later, it would be useful to design an assembly of the same type, but for a larger wind tunnel at higher velocities (for example, the S1 Modane tunnel which has a test section of 8 m diameter and a large velocity range), so as to permit tests for defining the influence of the Reynolds number on these coefficients.

The S1 Ch wind tunnel also has interesting characteristics in this respect.

7.3 Determination of the Aerodynamic Coefficients of Analytical Calculation from Overall Tests /11

Various methods are being developed at present to derive practical aerodynamic data in flight with full-scale aircraft (Ref.5, 6). Consequently, it seems of interest to apply these methods to lumped tests, either in a vertical tunnel or on catapulted models or else on models launched from helicopters (Ref.8).

The miniaturization of telemetry instrumentation permits the future use of accelerometric measurements, to replace the direct restoration of motions, which would prevent a double derivation and thus ensure more accurate calculations.

Nevertheless, despite these improvements, it is doubtful whether such a method will permit a sufficiently detailed determination of the aerodynamic coefficients.

In fact, practical experience has shown that, in some cases, one and the same set of responses in flight of the aircraft or of the model might be obtained with sets of different values of the aerodynamic coefficients.

Thus, such a quantitative method carries the risk of giving poorly defined values.

The advantage of the analytical method consists exactly in the possibility of imposing the variation of a single parameter while keeping the others constant, thus resulting in values of the corresponding coefficients without ambiguity.

Conversely, the measurement of certain coefficients is still impossible by analytical means.

8. Conclusions

The results obtained in a first phase of studying a computational method agree satisfactorily with measurements made on free-spin models in the vertical wind tunnel at the IMFL.

The method will be applied to comparisons of calculations with data obtained in flight of full-scale aircraft.

A typical example of such a comparison, using a method similar to that established by the ONERA, has recently been published by H.J.Wykes for the case of F-100 aircraft of North American Aviation, using nonstationary coefficients which were theoretically evaluated in a rather rough manner.

Facilities for analytical analysis at forced rotation have been investi- /12 gated and are in the practical development stage, which will permit further improvement of the evaluations.

Despite the fact that the above investigations concern the case of a flat spin of a delta aircraft as typical example, it is certain that the method is applicable to any other type of spin or aircraft.

Consequently, it can be hoped that aircraft designers will consider this method as a part of standard means for studying a given project.

REFERENCES /13

1. Scherer, M. and Louis, B.: Analytical Study of Spin (Étude analytique de la vrille). O.N.E.R.A., T.P. No.187, 1964.
2. Wykes, J.H. and Casteel, Gilbert R.: Comparison of Computer and Flight Test Results for a Spinning Airplane. North American Aviation, Los Angeles Division, AGARD F.M.P. Meeting, Cambridge, England, Sept. 1966.
3. Scherer, M.: Measurement of Aerodynamic Derivatives in the Wind Tunnel (Mesure des dérivées aérodynamiques en soufflerie). Publ. O.N.E.R.A., No.104, 1962.
4. Gobeltz, Jean: Development of Spin Testing Technique as a Function of Spin of Modern Aircraft (Évolution de la technique des essais de vrille en fonction des vrilles des avions récents). Tech. Mem. 6, Training Center for Experimental Aerodynamics, Rhode Saint-Genèse, Belgium, 1959.
5. Burns, B.R.A.: Experience with Shinbrot's Method of Transient Response; Analysis for the Extraction of Stability and Control Derivatives. British Aircraft Corporation, Preston Division, AGARD F.M.P., Cambridge, England, Sept. 1966.
6. Klopstein: Variable-Stability Aircraft and Flight Tests for Aerodynamic Coefficients (Avion à stabilité variable et mesures en vol des coefficients aérodynamiques). C.E.V., Istres, 3ème Colloque d'Aérodynamique Appliquée, A.F.I.T.A.E. [Third Colloquium of Applied Aerodynamics (AFITAE)], Istres, Nov. 1966.
7. Kappus, Robert: Method of Determining Inertia Constants by a Vibration Test on the Ground (Méthode de détermination des constantes d'inertie à l'aide d'un essai de vibration au sol). O.N.E.R.A., T.P. No.386, 1966.
8. Bisgood, P.L.: Low-Speed Investigations Using Freely-Flying Models. R.A.E. Bedford, AGARD F.M.P., Cambridge, England, Sept. 1966.

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